# Charmonium from CLEO

## Discovery of $h_c(^1P_1)$
## Two Photon Width of $\chi_{c2}(^3P_2)$

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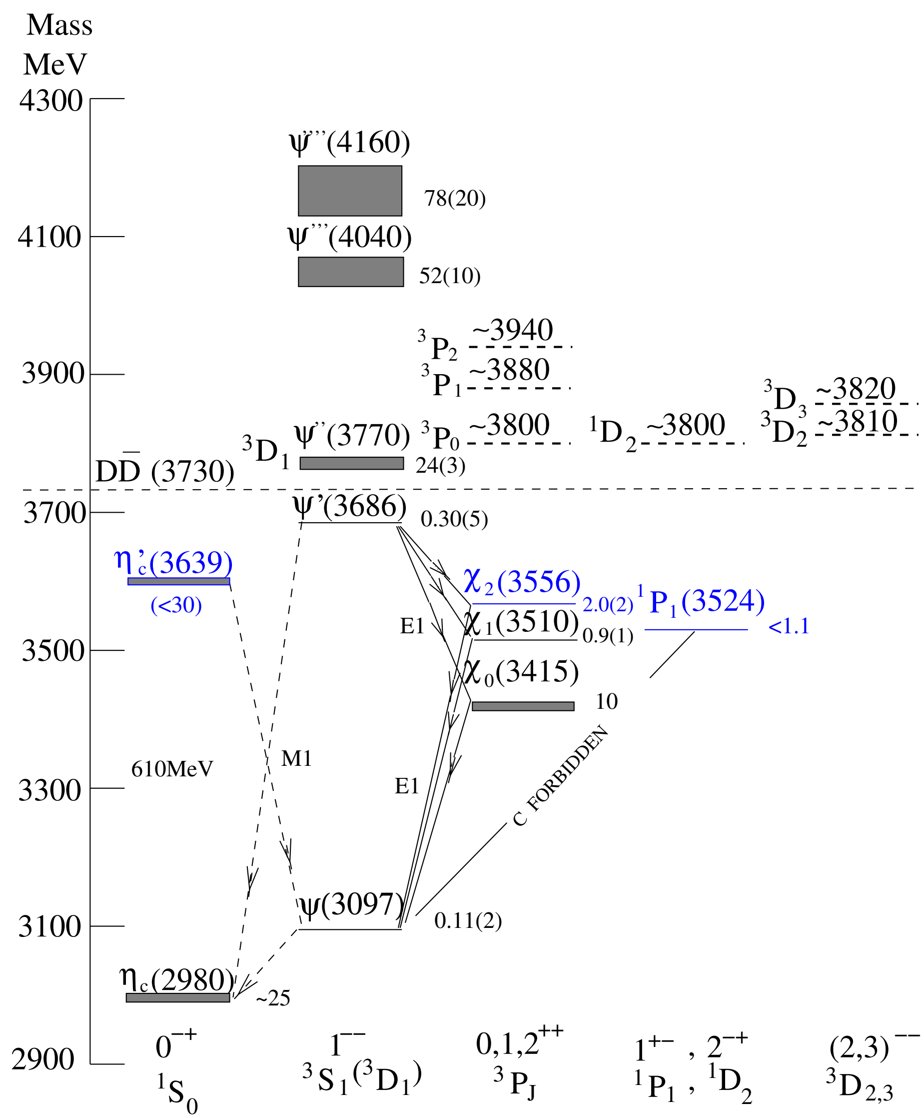
PANIC05
Sante Fe,
10/25/2005

# Introduction

- Quantum Chromodynamics, QCD, took foothold with the discovery of $J/\psi$, the spin–triplet S–wave state $(1^3S_1)$ of Charmonium. Over the next ten years SLAC and DESY successfully mined the rich load of charmonium spectroscopy with $e^+e^-$ annihilations. They did discovery level spectroscopy of the bound states of charmonium. In 1990 FNAL experiment E760 brough unprecedented precision to charmonium spectroscopy through $p\bar{p}$ annihilation.
- At the end of the 1990's, despite all the progress, certain nagging problems in charmonium spectroscopy remained. Among the most important of these were problems related to spin–singlet states and two–photon widths of $C+$ states.
- Neither the $e^+e^-$ or $p\bar{p}$ experiments were able to identify the S- and P-wave singlet states $\eta_c(2^1S_0)$ and $h_c(1^1P_1)$.These states are obviously extremely important for understanding the spin–spin hyperfine interaction of $q\bar{q}$.
- The two–photon widths of $C+$ states $\chi_{cJ}(^3P_J:\ 0^{++},\ 2^{++})$ are important for understanding relativistic and radiative effects in charmonia, because in the lowest order they are pure QED widths, akin to those of positronium levels. Unfortunately, results from different measuring techniques have remained very divergent for about twenty years.



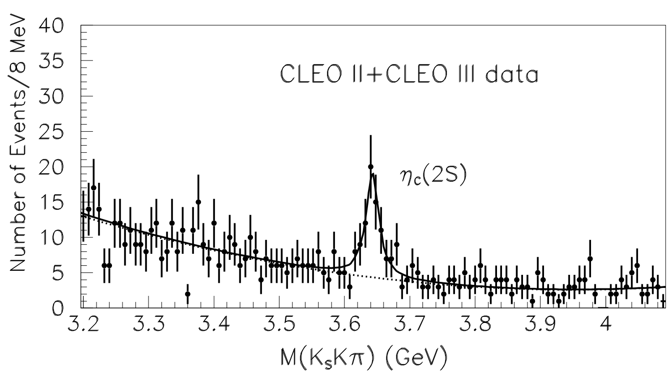

Charmonium Spectrum

# Discovery of $\eta_c(2^1S_0)$

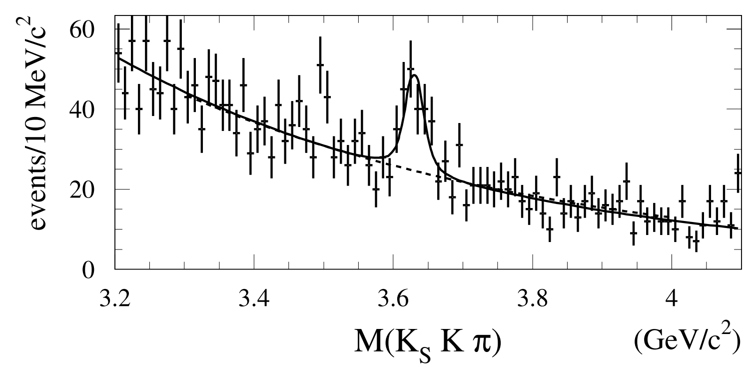
In 2002 Belle announced the discovery of $\eta_c(2^1S_0)$ in B decays as well as $e^+e^- \to J/\psi + c\bar{c}$. Unfortunately, the statistics in both measurements were small ($\sim 40$ counts) and $M(\eta_c(2S))$ values were quite different ($3654 \pm 10$ MeV, and $3622 \pm 12$ MeV). At CLEO [1] we identified $\eta_c(2^1S_0)$ in the two–photon fusion reaction $\gamma\gamma \to \eta_c(2S) \to K_S K\pi$, and determined the 2S hyperfine splitting

$$\Delta M_{hf}(2S) = M(\psi(2^3S_1)) - M(\eta_c(2^1S_0)) = 47.4 \pm 2.0 \text{ MeV},$$

an extremely interesting result, considering that $\Delta M_{hf}(1S) = 117 \pm 1$ MeV. At the same time BaBar [2] reported a similar observation of $\eta_c(2^1S_0)$.




CLEO: $M(\eta_c(2S)) = 3642.9 \pm 3.4$ MeV




BaBar: $M(\eta_c(2S)) = 3630.8 \pm 3.5$ MeV

## The Discovery of $h_c(1^1P_1)$

If the confinement potential is Lorentz scalar, there is no long–range spin–spin interaction in $q\bar{q}$. It follows that only S-wave hyperfine splitting, $\Delta M_{hf}(1S, 2S)$ is finite. For all other waves $(L \neq 0)$ hyperfine splitting is zero. In particular,

$$\Delta M_{hf}(1P) = M(\langle {}^3P_J \rangle) - M({}^1P_1)$$

To test this prediction it is necessary to identify $h_c(1^1P_1)$ and measure $M(h_c)$ with precision.

- In 1982 Crystal Ball [3] failed in the search for $h_c$ in the reaction $\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\eta_c$.
- In 1992 Fermilab E760 [4] studied the reaction $p\bar{p} \to h_c \to \pi^0 J/\psi$ and claimed the observation of a signal for $h_c$. However, higher luminosity runs in 1996 and 2000 have failed to confirm this observation.
- Fermilab E835 [5] has searched for $h_c$ in their 1996/2000 data in the reaction $p\bar{p} \to h_c \to \gamma\eta_c$.
  They report, $\Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2\ \mathrm{MeV}$, with 13 observed events and a significance of the $h_c$ signal at $\sim 3\sigma$ level.
- Now CLEO [6] has firmly identified $h_c$ with a significance level of $6\sigma$.

## CLEO Observation of $h_c(1^1P_1)$

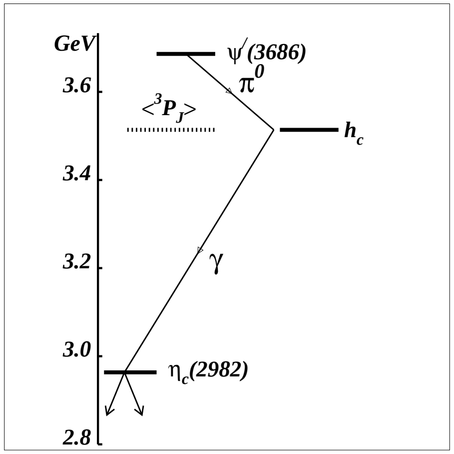
At CLEO-c data were taken at $\psi(2S)$, with 3.08 million $\psi(2S)$. These data have been analyzed for [6]

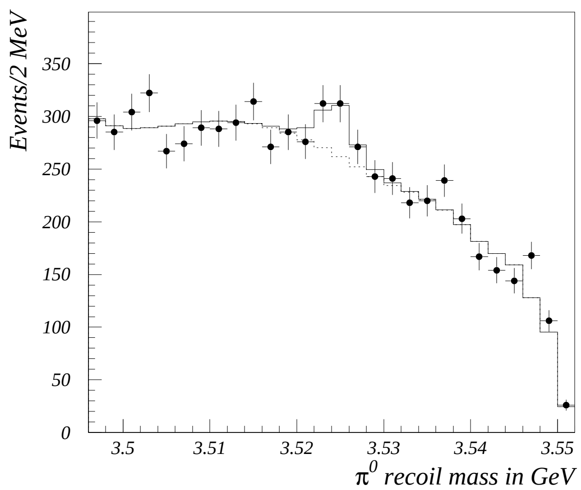
$$\psi(2S) \to \pi^0 h_c \ , \ h_c \to \gamma\eta_c$$

Both inclusive and exclusive analyses were done, and an accurate determination of $h_c$ mass was made in recoils against $\pi^0$'s whose energy could be measured with precision.

**Inclusive Analyses:** Two independent analyses, different in details of event selection and resonance analysis, were made. One constrained the photon energy $E_\gamma$, and the other constrained $M(\eta_c)$. Completely consistent results were obtained.

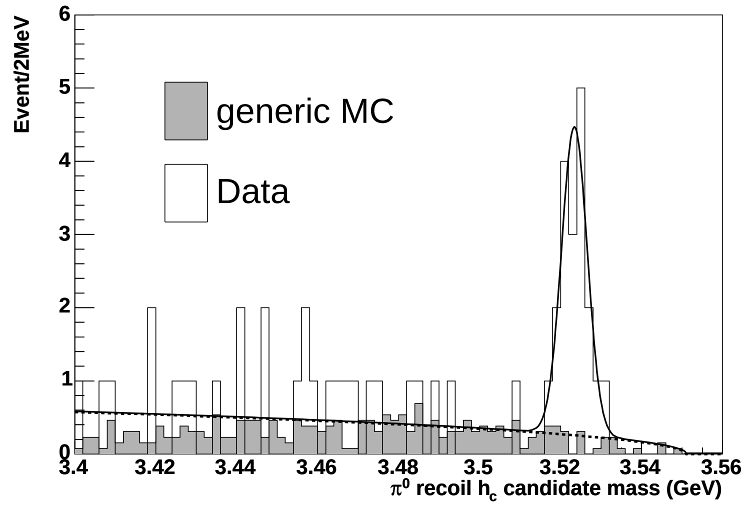
**Exclusive Analysis:** In this analysis, instead of constraining $E_\gamma$ or $M(\eta_c)$, seven known decay channels with a total branching fraction of $\sim 10\%$ were measured. Once again, consistent results were obtained.






INCLUSIVE

significance $= 3.8\sigma$




EXCLUSIVE

significance $= 6.1\sigma$

The overall result is

$$\boldsymbol{M(h_c) = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}, \text{ or}}$$

$$\boldsymbol{\Delta M_{hf}(1P) = \langle M(\chi_{cJ}) \rangle - M(h_c) = +1.0 \pm 0.6 \pm 0.4 \text{ MeV}}$$

E835 reports $\Delta M_{hf}(1P) = -0.4 \pm 0.2 \pm 0.2$ MeV.

Two conclusions follow:

- Simple pQCD expectation is not strongly violated.
- The magnitude and sign of $\Delta M_{hf}$ is not well determined.

## Two–Photon Width of $\chi_{c2}$

### A Bit of History

The table below illustrates the problem in the measurements of $\Gamma_{\gamma\gamma}(\chi_{c2})$ which I mentioned earlier. There are two different ways of measuring the two–photon width. In $e^+e^-$ collisions, the $\chi_{c2}$ state is formed in two–photon fusion, $\gamma\gamma \to \chi_{c2}$, and a subsequent decay of $\chi_{c2}$ (usually $\chi_{c2} \to \gamma J/\psi$) is measured. In $p\bar{p}$ annihilation, the $\chi_{c2}$ state is directly formed and its decay into two–photons is measured.

| $\gamma\gamma \to \chi_{c2} \to \gamma(l^+l^-)$ | $N$ | $\Gamma_{\gamma\gamma}$ (eV) |
|---|---|---|
| TPC(1993) | $6 \pm 3$ | $3400 \pm 1700 \pm 900$ |
| CLEO(1994) | $25 \pm 7$ | $1800 \pm 300$ |
| OPAL(1998) | 22 | $1760 \pm 470 \pm 370 \pm 150$ |
| L3(1999) | 14 | $1020 \pm 400 \pm 150$ |
| Belle(2002) | $136 \pm 13$ | $850 \pm 80 \pm 70 \pm 70$ |
| $p\bar{p} \to \chi_{c2} \to \gamma\gamma$ | $N$ | $\Gamma_{\gamma\gamma}$ (eV) |
| E760(1993) | 30 | $321 \pm 78 \pm 54$ |
| E835(2000) | $\sim 90$ | $270 \pm 49 \pm 33$ |

As shown in the table, the two–photon fusion measurements, including the latest one from Belle, yield two–photon widths which are three to ten times larger than the two–photon decay measurements of Fermilab. It is this persistent large discrepancy which motivated us to make the present measurement at CLEO [7].

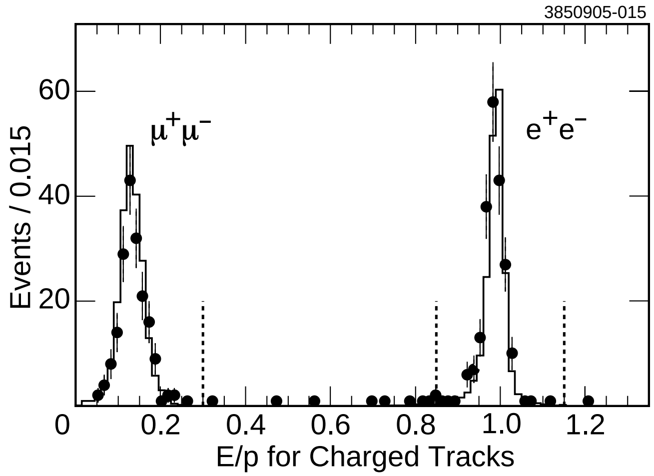
## Two–Photon Width of $\chi_{c2}$

We have used 14.4 fb$^{-1}$ of $e^+e^-$ data taken at CLEO in the Upsilon region, $\sqrt{s} = 9.46 - 11.30$ GeV, to study the two–photon fusion reaction

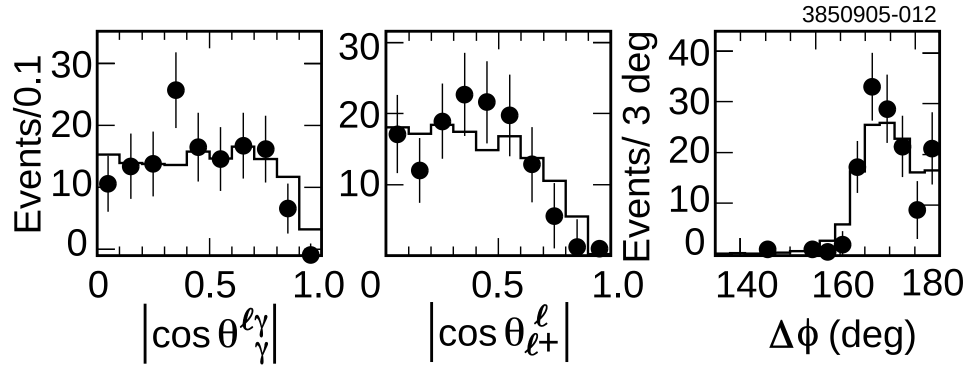
$$e^+e^- \to e^+e^- + \gamma\gamma,\ \gamma\gamma \to \chi_{c2} \to \gamma J/\psi,\ \ J/\psi \to e^+e^- + \mu^+\mu^-$$

| Data | $\mathcal{L}$ (fb$^{-1}$) | $\sqrt{s}$ (GeV) |
|---|---|---|
| $\Upsilon(1S)$ | 1.399 | 9.458 |
| $\Upsilon(2S)$ | 1.766 | 10.018 |
| $\Upsilon(3S)$ | 1.598 | 10.356 |
| $\Upsilon(4S)$ | 8.566 | 10.566 |
| $\Upsilon(5S)$ | 0.416 | 10.868 |
| $\Lambda_b\overline{\Lambda_b}$ | 0.688 | 11.296 |

Clean identification of $e^+e^-$ and $\mu^+\mu^-$ pairs is achieved.




The angular distributions of the photon and the leptons are found to be in good agreement with MC expectations assuming E1 radiative decay of $\chi_{c2}$.

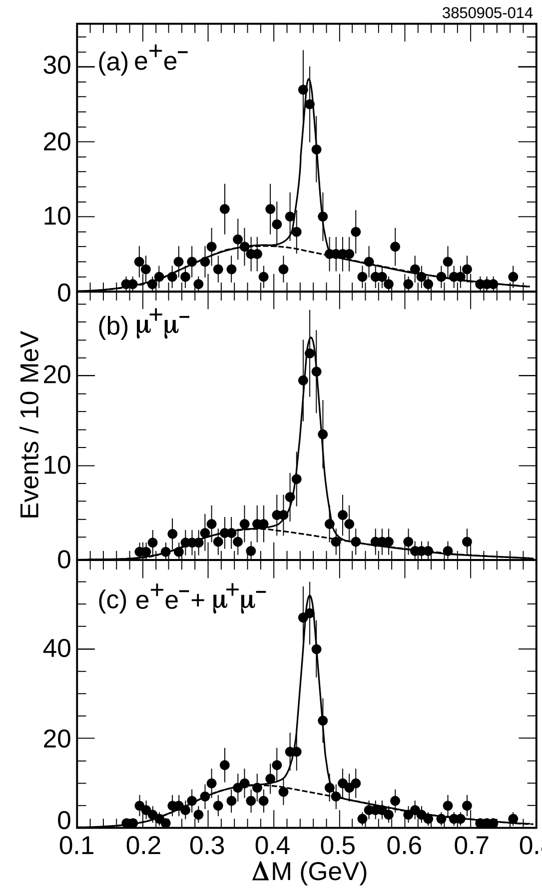


The photon mass spectrum

$$\Delta M \equiv M(\gamma l^+ l^-) - M(l^+ l^-)$$

shows clear peaks corresponding to the E1 photon from $\chi_{c2} \to \gamma J/\psi$. The fits to these peaks yield

| $l^+l^-$ | $N_{\rm obs}$ | $\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to \gamma l^+ l^-)$ (eV) | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV) |
|---|---|---|---|
| $e^+e^-$ | $68 \pm 11$ | $6.4 \pm 1.0$ | $544 \pm 87$ |
| $\mu^+\mu^-$ | $79 \pm 11$ | $6.8 \pm 0.9$ | $571 \pm 76$ |
| Total | $147 \pm 15$ | $13.2 \pm 1.4$ | $559 \pm 57$ |




The above result for $\Gamma_{\gamma\gamma}(\chi_{c2})$ is obtained from the measured value of $\Gamma_{\gamma\gamma}(\chi_{c2}) \times \mathcal{B}(\gamma l^+ l^-)$ by using the result for $\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ radiative decay from a recent CLEO measurement [8], which is quite different from the old CB result.

| | CB % | CLEO % |
|---|---|---|
| $\mathcal{B}(\chi_{c0} \to \gamma J/\psi)$ | $0.60 \pm 0.18$ | $1.95 \pm 0.24$ |
| $\mathcal{B}(\chi_{c1} \to \gamma J/\psi)$ | $28.4 \pm 2.1$ | $37.9 \pm 2.7$ |
| $\boldsymbol{\mathcal{B}(\chi_{c2} \to \gamma J/\psi)}$ | $\mathbf{12.4 \pm 1.5}$ | $\mathbf{19.9 \pm 1.7}$ |

## Comparisons

In making a comparison of the present results with other recent results, it was noted that the differences originate in using an old (PDG1990) value for $\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ which was nearly 40% smaller than the result of the new CLEO measurement. When the results of the Belle and E835 measurements are reevaluated using the CLEO value of $\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$, it is found that all results become completely consistent.

| Experiment<br>Quantity Measured | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV)<br>(as published) | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (eV)<br>(as reevaluated) |
|---|---|---|
| Present [7]: $\gamma\gamma \to \chi_{c2}$<br>$\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to \gamma l^+ l^-)$ | $\mathbf{559 \pm 57 \pm 48 \pm 36}$ | |
| Belle [9]: $\gamma\gamma \to \chi_{c2}$<br>$\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to \gamma l^+ l^-)$ | $850 \pm 80 \pm 70 \pm 70$ | $570 \pm 55 \pm 46 \pm 37$ |
| CLEO [10]: $\gamma\gamma \to \chi_{c2}$<br>$\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to 4\pi)$ | $530 \pm 150 \pm 60 \pm 220$ | |
| E835 [11]: $\bar{p}p \to \chi_{c2}$<br>$\mathcal{B}(\chi_{c2} \to \gamma\gamma)/\mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | $270 \pm 49 \pm 33$ | $384 \pm 69 \pm 47$ |

**Strong Coupling Constant**

Since the two gluon decay width of $\chi_{c2}$, $\Gamma_{gg}(\chi_{c2}) = 1.55 \pm 0.11$ MeV, our measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ allows us to estimate the strong coupling constant $\alpha_S(m_c)$. According to pQCD [12]

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{gg}(\chi_{c2})} = \frac{8\alpha^2}{9\alpha_s^2} \times \left( \frac{1 - \frac{5.33}{\pi}\alpha_s}{1 - \frac{2.2}{\pi}\alpha_s} \right).$$

Without the radiative correction factor in the parentheses, we obtain

$$\alpha_S = 0.36 \pm 0.03$$

With the radiative correction factor in the parentheses, we obtain

$$\alpha_S = 0.29 \pm 0.03$$

## References

[1] CLEO: PRL 92(2004)142001

[2] BaBar: PRL 92(2004)142002

[3] CB: Ann. Rev. Nucl. Part. Sci. 33(1983)143

[4] E760: PRL 69(1992)2237

[5] E835: PRD 72(2005)032001

[6] CLEO: PRL 95(2005)102003

[7] CLEO: hep-ex/0510033; Submitted to PRL

[8] CLEO: PRL 94(2005)232002

[9] Belle: PLB 540(2002)33

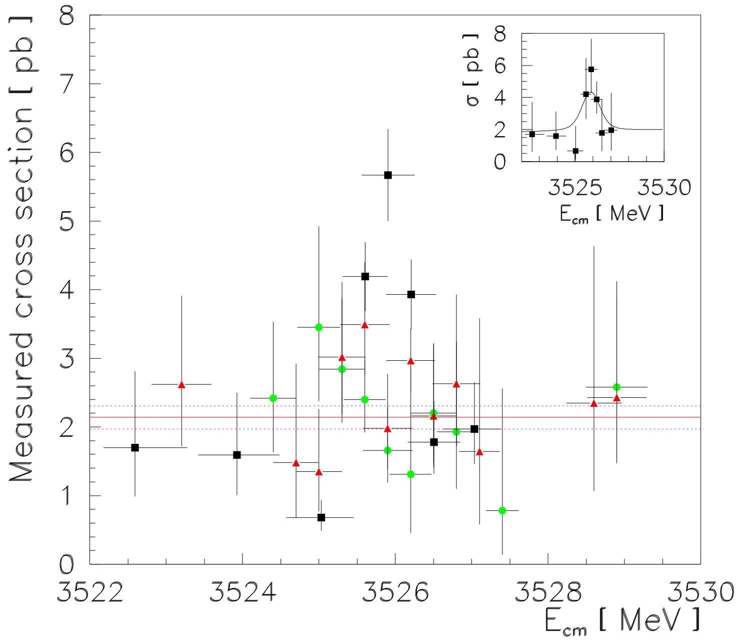
[10] CLEO: PRL 87(2001)061801

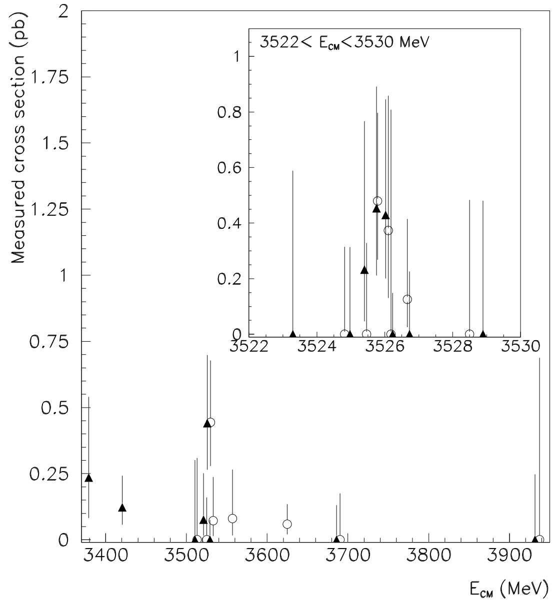
[11] E835: PRD 62(2000)052002

[12] PRD 37(1988) 3210

# Backup Slides

# Fermilab E835 Results for $h_c$ Search




E835 [1992+1996+2000]: $p\bar{p} \to h_c \to \pi^0 J/\psi$

No statistically significant signal

E835 [1996+2000]: $p\bar{p} \to h_c \to \gamma\eta_c$

$M(h_c) = 3525.8 \pm 0.2 \pm 0.2$ MeV

$13 \pm 4$ counts, significance $\approx 3\sigma$

squares (normalized E760 data), open circles (1997 data), triangles (2000 data)